PERFORMANCE STUDIES OF SUPERCONDUCTING DIPOLES FOR THE FERMILAB ENERGY DOUBLER

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March 1975

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Summary

The Energy Doubler magnet development and testing program was initiated in September 1972 and has thus far proceeded through three phases.[1,2] In the first phase, several wire winding geometries and the ability to reproduce magnet field properties in a pair of dipoles were explored. This phase closed with construction and operation of a 20 foot dipole magnet. When the 20 foot magnet did not perform to expectations phase 2, a program of 2.5 foot prototype construction, was initiated. Twelve 2½ foot magnets were tested to evaluate problems of excessive training and failure to go to short sample. Sufficient information was gained about mechanical structure, wire properties and coil cooling from these studies to cause an extensive redesign of the basic Energy Doubler dipole magnet.[2]

Construction of the first magnet of new design, C1 - 2.5, in October of 1974 marked the initiation of phase 3 of our program. Three magnets have now been completed: C1 - 2.5, a 2½ foot magnet, has gone to 40 kG mounted in a horizontal cryostat with warm iron. C2 - 2.5 has been used to explore some special concepts of coil confinement, and C2 - 10 has been tested by a 12,000 cycle test and excitation to 25 kG without iron as a demonstration of a magnet that would allow operation of the Doubler from 100 to 500 GeV in the "Energy Saver" mode.[3]

Reprise

In order to understand the context within which work on the C series of magnets has progressed, it is necessary to review what has gone before. Particularly since the present design draws on continuing experiments with the earlier 2½ foot prototypes.

Early Magnets

This work has been reported elsewhere in some detail.[1] To recapitulate, seven magnets were built to study various winding geometries for approximating the cosθ current distributions that produce dipole fields. It quickly became apparent that the shell type geometry gave magnets with superior performance to the pancake scheme of horizontally oriented, rectangular current blocks. Consequently, a pair of shell models were built and tested to evaluate the accuracy with which two magnets could be duplicated. This test and similar ones at Brookhaven National Laboratory were all completed at about the same time.[4,5]

Optimism, the desire to circumvent development delays and the high promise of the first superconducting wire designed specifically for Energy Doubler magnets led to the construction of full scale, 20 foot prototype dipoles. Three of these magnets were subsequently built and two tested electrically. Neither of the two magnets placed under electrical excitation performed satisfactorily. Both became superconducting but exhibited extensive training and failed to go higher than 55% of design field. The first magnet, tested in a horizontal dewar using pool boiling helium, provided useful information about the problems of combining cryogenics and electrical systems. The second was operated in the Energy Doubler prototype force-flow cooling loop, and while magnet performance was something of a disappointment, operation with the pump loop was very successful.[7]

*Operated by Universities Research Association, Inc. under contract with the U.S. Energy Research and Development Administration.

2½ Foot Prototypes

When performance of the first 20 foot magnet fell below expectations, a considerable redirection of resources into the 2½ foot model was initiated. At that time it was not clear whether the excessive training and failure to go to measured short sample were due to inadequate physical strength in the coil structure, inherent unknown problems with the superconducting wire or insufficient cooling within the coil structure. Ultimately, twelve models were used in a very complex parametric study of structure, wire and cooling problems. While these tests have been discussed previously, some additional data has been collected and so a summary of the testing has been included in Table I and figure 1.[2]

Magnets number 2, 4, 5 and 6b of the 2½ foot series have been rerun from time to time as part of the general development program. All of them continue to train upward, and all remember 85 to 90% of previous training. In particular, 2½ foot #5, now mounted in a horizontal dewar and used for development of field measurement apparatus, has, in over 300 quenches, trained up to a field of 31 kG and is still climbing. Since part of our concern over failure to reach short sample was based on the possibility of high field instabilities, the apparent lack of such an upper limit is encouraging. The operating date does not, however, preclude the possibility that high field stability problems will yet be encountered.

C Series Magnets

The present C series design, formulated in August and September of 1974, was intended to include 2.5, 10 and 20 foot magnets. A more conservative approach seemed appropriate. Consequently, the race track cross section bore tube used in 20 foot and 2½ foot prototypes was dropped in favor of a round bore tube that has a slightly larger inside coil diameter of 3 inches (see Table I). Since the measured short sample characteristic of delivered superconducting wire was below Fermilab specifications, the design operating current was lowered from 2600 to 2350 amperes. To fit the increased number of turns into the desired cross section required superconducting cable graded in two sizes and wound into four shells as shown in figure 2. The inner pair of shells use 0.075 x 0.150 inch cable and the outer 0.050 x 0.150. Barber pole insulation, 75% coverage, using B stage impregnated tape was retained from the 2½ foot 6 series design for superconducting cable insulation. Since one of the major concerns with our magnet designs has been manufacturing costs, and intermediate stainless steel banding between the inner and outer shell pairs represents a significant expense, the banding was, after much debate, omitted in favor of Scotchply fiberglass spacers.

C1 - 2.5

The first 2½ foot magnet of this series was tested in October in a vertical dewar without iron. A summary of magnet parameters, for comparison to the 2½ foot series, is included in Table I, and the quench data from the first two air core tests is included in figure 1. A complete quench history for C1 - 2.5 is shown in figure 3. In the 15 quenches run for this first test the magnet reached a maximum field of 36 kG and trained extensively. Quench origins were distributed almost equally between inner and outer shell pairs. A post test analysis indicated a turn-to-turn short had developed in shell 4B (4th shell outward radially and on the arbitrarily defined bottom of the magnet). Upon disassembling the magnet small balls of solder were discovered on the surface of some of the windings, indicating that excessive localized heating had occurred. In spite of all these problems the room temperature resistance of the magnet increased! C1 - 2.5 was quickly repaired. Only this time a stainless steel bore tube having ¼" wall thickness replaced the Scotchply-stainless steel tube structure used before, and stainless steel intermediate banding replaced the plastic spacers. A repeat test without iron showed some retraining and a peak field of 36.4 kG. Performance was acceptable and

Table I: Summary of Dipole Magnet Testing: 2½ foot and C Series

Magnet	Coil Data: No of Turns	Coil Data: No of Shells	Coil Data: Wire *	Principal Testing Goals for this magnet	No of Param. Tests[3]	Total No of Quench.	Percent of Short Sample[4]	Highest B(kG) Air/Fe
2½ # 1[1]	40	1	A	Change Structural Character by varying coil impregnation	4	40	92-A	17.8/26.0[5]
2	140	3	A,B	Similar to #1, but with 3 shells.	3	53	62-B	21.6/30[5]
3	140	3	A,B	Subλ, longitudinal "stick slip" friction and Energy Dump Testing	4	>200	74-B	25.9/-
4	154	4	A	Use of 4 shell magnet to lower current densities	6	77	61-A	27.0/-
5	154	4	A	Test of impregnation, long training, run psuedo long sample test, calibration magnet	18	>400	67-A	30.8/31.1[6]
6	82	2	C	1st test of cable, insulation and helium permeation.	1	8[7]	78-C	26.0/-
6a	164	4	C	1st use of intermediate s.s. bands and Aluminum outer rings	2	14[7]	80-C	33.2/-
6b	164	4	C	Repeat of 6a	3	66[7]	83-C	34.5/-
6c	164	4	C	Repeat of 6b. Used s.s. bands vice rings. Fully impregnated	1	45[7]	82-C	- /37[5]
7	154	4	A	Vacuum impregnation, 1500 psi curing, Al rings - a rigidized magnet	1	81	63-A	27.3/-
8	200	6	A	To get B>40 kG	1	106	82-A	- /37[5]
9	78	2	E	Test helium permeation on solid Cu matrix wire	1	38	71-A	23.0/-
C1 - 2.5[2]	228	4	C,D	Prototype 45 kG magnet	3	65	87-B	36.4/40.4[6 7]
C2 - 2.5	228	4	C,B	Evaluate intermediate s.s. banding and aluminum outer rings.	3	72	76-B	33.5/-
C2 - 10	214	4	C,D,F	10 ft. prototype Energy Saver magnet	2	14	64-B	25.4/-

*wire key	Nominal size (in)	Number Strands	Filaments/ Strand	Filament size (μ)	Copper: S.C.	Twist (turns/in)	Insulation Type	Filler (cable only)
A	0.150x0.075	1[8]	2300	~35	2:1	1/1	Formvar type	-
B	0.150x0.050	1	2300	~23	2:1	1/1	Formvar type	-
C	0.150x0.075	7[9]	520/1050	29,21 mixed	1:1	2/3	75% Barber Pole	60/40:Pb/Sn
D	0.150x0.050	11[9]	520/1050	20,15 mixed	1:1	2/3	75% Barber Pole	60/40:Pb/Sn
E	0.150x0.075	1[8]	2300	~35	2:1	1/1	75% Barber Pole	-
F	0.150x0.050	11	162	28	2.2:1	2/1	75% Barber Pole	95/5:Sn/Ag

1. Bore tube for all 2½ #n series: 2.500 x 1.7500 inch race track cross section.
2. Bore tube for all C series: 3.000 inch inner wire diameter, round cross section.
3. This is the number of major different magnet configurations tested as part of the program of parametric evaluation.
4. Field measured on the "worst" wire divided by the Critical Field measured at the intersection of the short sample curve and the B = KI line for that wire. The letter indicates which type of wire limits operation.
5. Bore field. Tests were done with a "close", cold iron which is in the helium, goes into partial saturation but is not used for structural support.
6. Bore field data for regular warm iron.
7. Magnets burned out.
8. Monolothic, solid copper matrix.(see Reference 7).
9. Rutherford style cable, hollow core, flattened. (see Reference 7).

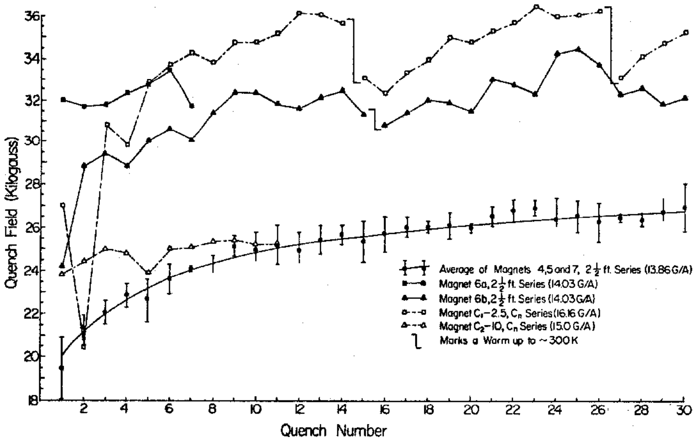

Figure 1. Performance of selected prototype magnets: air core operation, data limited to the first 30 quenches.

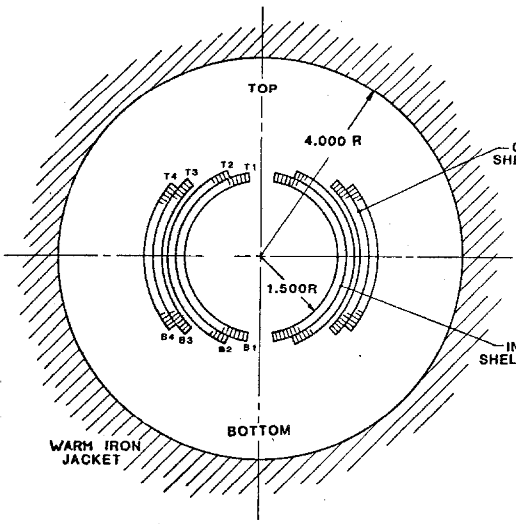

Figure 2. Cross section of C series magnet.

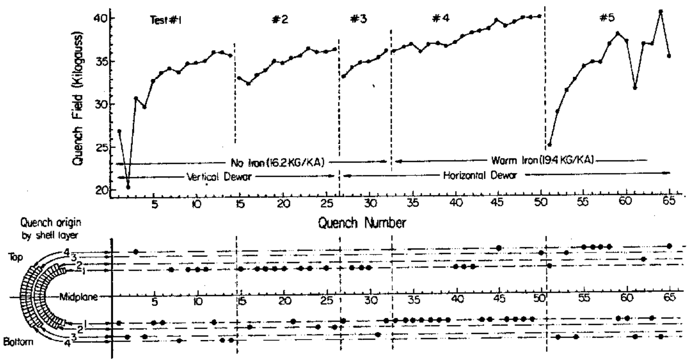

Figure 3. Performance history of magnet C1 - 2.5.

the magnet was installed in a horizontal dewar, where a no iron transfer function of 16.2 G/A was measured. The addition of the warm iron for test #4 showed a surprising field continuity in going from no iron to 20% iron enhancement, especially in view of the partial retraining required at the start of Test #3. This is the first magnet in our program to exhibit significant loss of training in a warm-up to room temperature. As figure 3 shows, the magnet trained slowly in Test #4 to 39.6 kG; it then burned out. Post test analysis attributed the failure to the barber pole insulation which was crushed by magnetic forces at the high field causing a short in coil 3T. Damage was severe enough that coil 3T had to be rewound. Test #5 then saw severe retraining, a phenomena confirming previous observations that disassembling a magnet does not generally destroy remembered training unless the windings themselves are disturbed. Since the winding tension on the stainless steel banding was considerably higher in this reconstruction, and all banding was sandblasted and coated with epoxy during assembly, significantly improved performance was expected. Unfortunately, shorts developed in several windings during assembly. The decision was made to proceed with the test anyway, but perhaps the training would not have been so severe if the shorts had not been present. In any case the shorts finally caused the magnet to fail but not before reaching 40.4 kG at 2080 amperes.

C2 - 2.5

This magnet was used primarily for parametic evaluation of structural changes, and no quench plots are included. It was wound with 7 strand 0.075 x 0.150 inch cable in the inner two shells and 0.050 x 0.150 inch solid copper matrix wire in the outer two shells. The wire used in the outer shells is from the material inventory for 20 foot outer shells and does not perform as well as 11 strand cable of similar dimensions. Except for the wire used in shells 3 and 4, this magnet was constructed similar to C1 - 2.5 as used in Test #1 of figure 1. The magnet exhibited extensive training with a curve sloping about the same as C1 - 2.5 but displaced ~8 kG downward. After 61 quenches of trouble free operation, the magnet, which had trained to 25 kG, was rebuilt with highly tensioned, sand blasted and epoxy coated intermediate stainless steel banding to constrain shells 1 and 2 and aluminum rings 3/4" thick radially and 3/8" longitudinally to hold shells 3 and 4. In the retest a significant performance change was observed. There was almost complete memory, all quench origins moved from about an even inner-outer shell distribution to the outer shells and training, while so severe as to have an almost linear characteristic, had a higher slope than in the first test. The highest field reached was 33.5 kG on the 22nd and last quench of the test. Since this magnet was destined to be placed in the Main Accelerator for operational tests, the aluminum rings had to be replaced with stainless banding. For comparison purposes another series of 33 quenches were run. Some loss of memory was exhibited and training was slower but still almost linear. Quench origins remained in the outer shells implying that the improved intermediate banding was immobilizing the turns in the inner shell more effectively. While training with a magnet constructed with solid matrix wire is more severe due to stability problems, the field ultimately reached by C2 - 2.5, 34.6 kG, was almost as high as the 36 kG achieved without iron in C1 - 2.5.

C2 - 10

Changing budgetary circumstances, both with regard to funds available for the Energy Doubler and to the Fermilab monthly power bill, resurrected interest in the Energy Saver mode of operation described in the review paper by Edwards et al.[4] Here operation of the superconducting magnet ring would range from 100 to 300 GeV, at injection from the Main Ring, to 400 to 500 GeV final energy. If the ramp were from 300 to 400 GeV the cycle time could be quite short, ~12 seconds, while maintaining a modest di/dt implying minimum contribution to the heat load from ac losses. A superconducting accelerator operating in this mode would enable Main Accelerator power costs reaching 400 GeV to be reduced by a factor of three. This reawakened interest in the Energy Saver, coupled with the relatively successful operation of C1 - 2.5 made construction of a 10 foot prototype seem desireable and timely.

C2 - 10 uses almost the same cross sectional design, shown in figure 2, as C1 - 2.5. Since the thickwall bore tube did not seem to change performance in C1 - 2.5, the design returned to the thinwall stainless steel bore tube wound with Scotchply to a ¼ inch wall thickness. High tension, sand blasted and epoxy coated banding was retained for both inner and outer mechanical confinement. A special feature was the availability of new 11 strand 0.050 x 0.150 inch cable from our wire development program.[7] This was marred only by a shortage of the new wire which necessitated introducing 4½ turns of an older, lower quality cable in shell 4B. The top 10 turns of 11 strand cable used in shells 3B and 3T, which are in a very high field region, were replaced by 0.075 x 0.150 inch 7 strand cable. Packing an equal number of turns of the larger wire into the space allowed was not possible, and a total of 14 turns had to be sacrificed in shells 3 and 4, yielding 214 turns instead of 228, and reducing the transfer function without iron from 16.2 G/A to 15.0 G/A (see Table I). The insulation problem discovered in testing C1 - 2.5 had prompted a careful investigation of the properties of the Fuseflex tape used. This material consists mostly of Dacron and B-stage epoxy with about 10% or less of glass and tends to flow during curing, losing much of the incompressibility necessary to maintain wire positions. A switch to a tightly woven tape with very high glass content, impregnated with only the minimum amount of epoxy required for bonding, gave promise of improvement in mechanical and electrical integrity of the new magnet.

For the first time in the C series of magnets an independant operating test of inner shell pairs was conducted. Reaching 2470 amps on the third quench, the magnet would undoubtedly have gone to much higher currents, but an arbitrary ceiling of 2500 amps, reached on the fourth trial, had been imposed. Ramping was then successfully performed up to a di/dt of 100 A/second, encountering no indication of the sort of ramp sensitivity that means shorts are present.

Operation of a C series magnet at Energy Saver field levels is very conservative. The ability to operate at higher ramp rates was not so obvious, nor was the durability of the design. Consequently, testing of C2 - 10 aimed primarily at measuring durability at ramp rates and fields needed for Energy Saver operation, and so 12,385 ramp cycles were run on the magnet in four days. A summary of various ramp cycles employed in the test is presented in Table II. The nominal flat top current was arbitrarily set at 1400 amps. However, in setting up the first ramp, the magnet was excited to 1590 amperes (23.8 kG) before quenching. The first test of an acceptable accelerator magnet, no training up to operating field, was therefore passed. Operation in this mode presented no magnet associated problems or any sign of deterioration in performance. On the fourth day 11 quench cycles were run to test the high field limit. Unfortunately the magnet would not go above 25.4 kG (570 GeV), but all the quenches originated in coil 4B, the one containing 4½ turns of substandard superconducting wire.

Table II: Summary of ramps and ramp rates used in 12,000 cycles life test of magnet C2 - 10

Ramp #	Shape	Per. (sec)	Inj.* (GeV)	Peak* (GeV)	$\frac{di}{dt}$	No. of cycles
1	trap.	29	100	470	95	2803
2	trap.	25	100	470	110	2197
3	trap.	12	300	470	113	6347
4	tri.	6	300	400	70	734
5	tri.	5	300	400	84	170
6	tri.	4	300	400	105	135

(trap. = trapezoid; tri. = triangular)

*Based on $E \approx PC = 22.4$ B(kG) for the Main Ring and Energy Doubler/Saver.

One interesting aspect of this test was instrumentation in the form of electret microphones operating in the helium bath which allowed audio monitoring of magnet behaviour. Clearly audible were helium boiling associated with ac losses generated during a ramp and stress adjustments in the form of sharp pinging sounds associated with the fracture of epoxy bonds under shear loading.

Conclusion

The Cn series of magnets have been a significant step toward a 20 foot, 45 kG Energy Doubler magnet. Performance which is dependent on structure, wire and insulation is better understood. Conclusions from previous work, adequacy of stainless steel banding, use of intermediate banding, the undesireability of excessive amounts of epoxy, the bad performance of epoxies under shear stress, the importance of helium permeation for cooling, the necessity for small superconductor filament size, the importance of wire stability, all have been confirmed in varying degree. In addition, a serious problem with insulation seems to have been solved.

There are still many problems. The adequacy of the magnet structure is still suspect because of the training. Analysis of the field to measure harmonic content as a function of magnetic field is an urgent project that needs completion and should provide useful information about structure deformation under loading from the magnetic forces.

Acknowledgements

A program of this magnitude rests heavily on the dedicated efforts of many persons. We would particularly like to acknowledge the special efforts of the magnet construction personnel under Will Hanson and Rolf Brocker. The pleasant and continuing council and guidance of Paul Reardon and Bill Fowler are much appreciated. Regretfully, one our co-authors, Darrell Drickey, who spearheaded the Cn series magnet design, passed away in December 1974. His infectious enthusiasm for the whole program will be missed.

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